Efficient Quantification Using Local Information for Cooperative Spectrum Sensing in Cognitive Radio

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***Abstract*—Cooperative spectrum sensing, a key technology in cognitive radio, has to summarize all the detection information from cognitive terminals without licensed band. In order to employ both reliable and efficient transmission of overhead, this paper seeks a way of quantifying the detection information with variable length to save the spectrum resource as much as possible. Analysis and simulation show the detection performance of our scheme is similar to the optimal linear combination scheme and much higher than the "OR" combination one, and even the total overhead does not increase significantly than the "OR" combination scheme.**

Keywords-cooperative spectrum sensing; log-likelihood ratio; overhead bits; cognitive radio

I. INTRODUCTION

A great deal of spreading wireless application has brought increasingly rare non-renewable spectrum resources, but Federal Communications Commission's (FCC) survey indicates such an inefficient use [1], which is a dilemma invoking cognitive radio (CR) [2] as significant candidate technology for the improvement of spectral efficiency. Cognitive radio, the updated version of software defined radio, finds out the licensed but idle band and serves the users with optimized parameters after the perception of the changing wireless environment. It "filches" the licensed spectrum band without interfering primary system rather than the allocation of new band, determined by its working principle.

Cognitive radio, an emerging research topic, is facing many technological challenges, such as spectrum sensing, spectrum sharing, spectrum decision, and spectrum mobility [3]. Spectrum sensing receives more attention as one of the attributes of cognitive radio and the premise of cognitive application. In order to sense primary user (PU), three sensing methods have been proposed- energy detection, matched filter detection and feature detection [4]. In addition, the combination of them is recommended for their own advantages. However, for a single CR user who is also called *secondary user* (SU), high and stable detection performance is difficult to reach, whatever detection method is adopted, and thus that a volume of SUs cooperated together to detect PU's existence is drawing more attention.

A relay-based cooperative scheme for two-user and multi-user was proposed in [5] and [6] respectively by Ghurumuruhan Ganesan et al. [7] proposed two cooperation protocols to improve the detection probability compared with an existing protocol. Zhi Quan et al [8],[9] suggested an optimal linear combination scheme for cooperative sensing. However, these approaches did not consider the transmission of detection information in band limited CR system. Jun Ma et al [10] proposed a new softened hard combination scheme with two-bit overhead for each user and achieved a good trade-off between detection performance and complexity. Chunhua Sun et al [11] have employed a censoring method with quantization to decrease the average number of sensing bits to the common receiver. Nevertheless, the detection performances in these bibliographies are not good enough due to the simple quantification scheme, and they did not mention how to transmit these quantified bits through air interface since CR system has no licensed band.

In the paper, we have established a set of practical methods to sense and implement cooperation in cognitive radio. A variable length quantification (VLQ) scheme based on log-likelihood ratio detection is proposed as a trade-off between detection performance and overhead. Compared to traditional "OR" method and linear combination schemes in many literatures, the VLQ of every user's detection log-likelihood ratio (*LLR)* has more advantages in efficiently using the rare spectral band for CR system, which not only improves detection performance more remarkably than the "OR" method but also restricts necessary overhead bits to a small quantity. Although it is quite difficult to transmit stably and reliably in CR system without licensed band, the overhead with lower transmission rate can be successfully submitted by using our proposed way in [12].

The rest of the paper is organized as follows. Section II introduces the system model, and two traditional cooperative sensing schemes are given. And then, the VLQ scheme is

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proposed in section III. Simulation results with corresponding analysis are given in section IV. Section V concludes our work.

II. SYSTEM MODEL

Cooperative sensing with multiple SUs and one PU is considered in our approach. Fig.1 shows the fundamental scenario of cooperative sensing where *N* SUs firstly implement sensing process independently, and then all the detection information is summarized by *Fusion Center* to make a final judgment.

The binary hypothesis ($\mathcal{H}_0$ denotes PU is not working, while $\mathcal{H}_1$ is the alternative hypothesis) is adopted in our study, so the received energy at user *k* can be given by:

$$r_k = \begin{cases} \sum_{j=1}^{M} \frac{\left(n_{k,j}\right)^2}{\sigma_k{}^2} & \mathcal{H}_0 \\ \sum_{j=1}^{M} \frac{\left(h_k s + n_{k,j}\right)^2}{\sigma_k{}^2} & \mathcal{H}_1 \end{cases} \qquad (1)$$

where $n_{k,j}$ is the received noise at *j*-th sample of *k*-th user. h_k is the channel gain from PU to the *k*-th SU. *S* is the transmit signal of PU, and *M* is the sampling number. $\sigma_k{}^2$ is the deviation of *k*-th user's noise. Since the $n_{k,j}$ is assumed to follow Gaussian distribution, the r_k follows central or non-central chi-square distribution respectively when $\mathcal{H}_0$ and $\mathcal{H}_1$ with *M* degrees of freedom (2).

$$r_k = \begin{cases} \chi_M^2 & \mathcal{H}_0 \\ \chi_M^2\left(\lambda_k\right) & \mathcal{H}_1 \end{cases} \qquad (2)$$

We defined the $\gamma_k = \frac{1}{M}\sum_{j=1}^{M}\left|h_k s\right|^2$ as the instantaneous SNR of the *k*-th CR user. The non-centrality parameter $\lambda_k = M\gamma_k$.

A. Conventional Schemes

"OR" Combination Scheme:

In conventional CR system, an energy threshold value helps the distributed SU make its local decision; for example, the energy detection alarm will be submitted to the *Fusion Center* when the measured energy level of a SU is higher than the threshold value. When one SU reports alarm, the *Fusion Center* regards the system-wide alarm as issued. This type of cooperative sensing scheme, sometimes called "OR" or hard combination scheme, has the advantage of low complexity for easy realization with less exchanging information saving the rare achievable band in CR system, but it is weak for the poor performance. Only when a relatively large number of users are cooperating, can better detection effect be achieved [13]. Besides, the combined individual user's binary decision may result in overstated false alarm of poor performance users and shrink true detection of good performance ones. If the energy threshold equals r_{th} , the false alarm and miss detection probability of hard combination scheme are given by (3) and (4) respectively.

$$P_{FA} = p\left(\exists r_k > r_{th} \mid \mathcal{H}_0, \forall k = 1,2,\cdots N\right) \qquad (3)$$

$$P_{MD} = p\left(\forall r_k < r_{th} \mid \mathcal{H}_1, \forall k = 1,2,\cdots N\right) \qquad (4)$$

Linear Weighted Combination Scheme:

Many literatures have introduced cooperative sensing [7]-[9] in the manner of linear combination, a cooperative way that requires all the users' received energy as well as their SNR for superior detection performance to present the weight coefficient of the former one in the final fusion result. Despite the high performance the manner brings, it is a challenge for the CR system without licensed band for volumes of overhead information like received energy and SNR of each SU needing to be updated correctly at *Fusion Center* are transmitted through air interface.

For example, in [10] the miss detection probability and the corresponding weight coefficient of linear weighted combination scheme are given by (5) and (6) respectively.

$$P_{MD} = 1 - \mathrm{Q}\left(\frac{\mathrm{Q}^{-1}\left(P_{FA}\right) - \sqrt{M/2}\sum_{k=1}^{N} w_k \gamma_k}{\sqrt{\sum_{k=1}^{N} w_k^2\left(1+2\gamma_k\right)}}\right) \qquad (5)$$

$$w_k^* = \frac{\gamma_k}{\sqrt{\sum_{k=1}^{N}\gamma_k^2}} \qquad (6)$$

III. EFFICIENT QUANTIFICATION FOR OVERHEAD

A. Log-likelihood Ratio Detection

If the *Fusion Center* can acquire all the information from each SU, the system log-likelihood function can be given by:

$$LLR = \log\frac{p\left(\mathbf{r}\middle|\mathcal{H}_1\right)}{p\left(\mathbf{r}\middle|\mathcal{H}_0\right)}, \qquad (7)$$

where $\mathbf{r} = \{r_1, r_2, \cdots, r_N\}$. Luckily, the received energies of different SUs are independent to each other (usually they are far away each other), so the *LLR* expression can be given by:

$$LLR = \sum_{k=1}^{N}\log\frac{p\left(r_k\middle|\mathcal{H}_1\right)}{p\left(r_k\middle|\mathcal{H}_0\right)} \qquad (8)$$

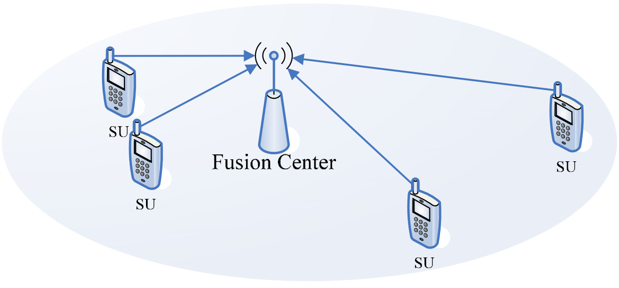

Figure 1. Cooperative sensing scenario

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Due to the central and non-central chi-square distributions, the probability density function of r_k can be expressed as:

$$p\left(r_k \middle| \mathcal{H}_0\right) = \frac{1}{2^{\frac{M}{2}} \Gamma\left(M/2\right)} r_k^{\frac{M}{2}-1} e^{-\frac{r_k}{2}} \tag{9}$$

$$p\left(r_k \middle| \mathcal{H}_1\right) = \frac{1}{2} e^{-\frac{\left(r_k+\lambda_k\right)}{2}} \left(\frac{r_k}{\lambda_k}\right)^{\frac{M}{4}-\frac{1}{2}} I_{\frac{M}{2}-1}\left(\sqrt{r_k \lambda_k}\right), \tag{10}$$

The $I_a\left(y\right)$ is the Bessel function expressed as:

$$I_a\left(y\right) := \left(y/2\right)^a \sum_{j=0}^{\infty} \frac{\left(y^2/4\right)^j}{j!\Gamma\left(a+j+1\right)} \tag{11}$$

The *LLR* at user *k* can be given by (12), and detailed deduction is given in the appendix.

$$LLR_k = \log\left(\frac{p\left(r_k \middle| \mathcal{H}_1\right)}{p\left(r_k \middle| \mathcal{H}_0\right)}\right) \approx \frac{1}{2}\gamma_k M\left(\overline{r_k}-1\right) \tag{12}$$

If each SU submits its local *LLR* to the *Fusion Center*, the total *LLR* will be:

$$LLR = \sum_{k=1}^{N} LLR_k \approx \frac{1}{2}\sum_{k=1}^{N} \gamma_k M\left(\overline{r_k}-1\right) \tag{13}$$

It is clear that the total *LLR* can be viewed as the linear combination of $\overline{r_k}$ s. The combination weight coefficient $\gamma_k M$ is similar to the optimal weight in [10]. This result gives us an idea that contribution of each SU in a cooperative process not only depends on the received energy but also the received SNR and total sampling number *M.*

It makes sense that some of calculation for optimal combination can be dealt with at individual SU. Therefore, a large amount of overhead transmission is unnecessary. Based on the above analysis, our proposed cooperative sensing method and corresponding quantification scheme for detection information will be given as follows.

B. *Variable Length Quantification (VLQ) for LLR*

From equation (13) we can see that part of the optimizing operation can also be handled by local SUs, which means it is unnecessary to submit all the local information to the *Fusion Center*, which could waste spectrum resources. The absolute value of local *LLR* of user *k* indicates its significance among all ones, so the less significant ones should be quantified with less bits, while more significant ones with more bits.

$$LLR_k^c = LLR_k \cdot c \tag{14}$$

$$LLR_k^D = \left\langle LLR_k^c \right\rangle \tag{15}$$

$$L = \begin{cases} \left\lfloor \log_2 \left|LLR_k^D\right| + 1 \right\rfloor & LLR_k^D \neq 0 \\ 0 & LLR_k^D = 0 \end{cases} \tag{16}$$

$$\widehat{LLR_k} = \begin{cases} f_{D\to B}^{L}\left(LLR_k^D\right) & LLR_k \geq 0 \\ f_{D\to B}^{L}\left(2^{\left\lfloor \log_2 \left|LLR_k^D\right|+1\right\rfloor} - 1 - LLR_k^D\right) & LLR_k < 0 \end{cases} \tag{17}$$

$\left\langle \bullet \right\rangle$ indicates the closest integer with $\bullet$

$\left\lfloor \bullet \right\rfloor$ indicates the highest integer smaller than $\bullet$

$f_{D\to B}^{L}\left(D\right)$ is a function that transforms decimal *D* to binary one with *L* bits.

(14-17) show our proposed quantification scheme. The *LLR* of user *k* (LLR_k) times a *compression ratio c* (*c*>0) is the coded *LLR* (LLR_k^c) before an integer LLR_k^D approximately closest to LLR_k^c is selected. Different *LLR* is quantified by a diverse length determined by (16). Finally, (17) enables us to translate decimal *LLR* into *L*-long binary bits. The formulae point out that the primary digit of final binary serial is '1' for positive *LLR* and '0' for negative *LLR*.

For example, the LLR_k for a single SU is -0.76, and the *c*=10. Therefore, LLR_k^c=-7.6, LLR_k^D=-8, *L*=4, $\widehat{LLR_k}$ ="0111". In addition, if LLR_k^D equals zero, the *L* will be zero too, which means the SU would submit nothing to the *Fusion Center*. In other words, if the detection information of a certain SU is not usable, it won't waste any resources at all.

It is clear that the length of coded bits for each SU depends on both the absolute value of local LLR_k and *compression ratio*. These two parameters bring corresponding benefits respectively. One is that the user-specified LLR_k makes it possible to submit variable length overhead bits from different SUs according to their detection reliability (such as SNR and sampling number) and current detection results. The other is that the system uniform *compression ratio* controlled by *Fusion Center* can be used for adjusting the system average overhead information, and this value can also affect the detection performance which will be shown in the next section.

Since only *LLR* is transmitted, overhead transmission by our proposed approach is less than that by linear combination one. Moreover, the *LLR* is much easier to be quantified for it is just a ratio different from received energy or SNR. Although *LLR* transmission produces more overhead than "OR" scheme, we can confine it to a small scope by *compression ratio c* without interfering the PU, which will be covered in the next chapter. Nevertheless, our proposed method still has some problems. Firstly, the terminal becomes more complex because of the secondary users' local calculation and processing. However, as far as CR itself, SUs are endowed with more remarkable intelligence than traditional terminal and terminal operation has been simplified to a certain extent by our simplified formula. Secondly, how to decide the threshold determining whether the PU is available or not at *Fusion Center* is an issue for this algorithm whereas the threshold can be modified by false alarm probability estimation in terms of CR system interfered by the PU.

Fig.2 provides a direct way for us to understand the three preceding cooperative approaches. The leftmost "OR" combination scheme needs one bit decision to be transmitted back to *Fusion Center*, while the rightmost linear combination approach does not require any local processing (some necessary quantification process is needed), but directly transmits a large volume of local information back to *Fusion Center*. However, our proposed method (the middle one) requires not only SU local calculation and processing, but also less information back to *Fusion Center* from SU than that by the way of linear combination and different information volume transmitted by every SU.

IV. NUMERICAL SIMULATION

In order to compare our cooperative scheme with conventional ones, we give the numerical results for *receiver operating characteristics* (ROC: probability of miss detection vs. probability of false alarm) of each scheme. We assume that five SUs are cooperating in this simulation, and the average SNR and sampling number for them are -8dB and 100 respectively. As is shown in Fig.3, the proposed quantification scheme outperforms the "OR" combination one a lot, while approaching the optimal linear combination one when the *compression ratio* equals one. However, when the relatively low *compression ratio* (*c*=1/5) is operated, the ROC is also much better than the "OR" combination.

Fig.4 gives us a clear recognition of how much bits should be transmitted when using the proposed scheme. The value of 1 and 1/5 represents the high *compression ratio* and low one respectively. Unlike the "OR" combination scheme, the average length of overhead bits are dynamic corresponding to the SNRs of SUs. Furthermore, the average lengths under two hypotheses are not similar either.

It is a trade-off between detection performance and overhead average length by adjusting the *compression ratio*. If the SNR is relatively low (lower than about -8dB), although high *compression ratio* is employed for offsetting the degradation of detection performance, the average length can be maintained within about 2 bits. The low *compression ratio* would be used to shorten average length when the average SNR is relatively high. In this condition, although the lower *compression ratio* can deteriorate the ROC, it is not a disaster due to the high average SNR. In addition, the overhead with little bits can be nearly non-interfered submitted by using our work in [12].

V. CONCLUSION

In this paper aiming at the disadvantages of the traditional hard combination and linear combination schemes, we propose a variable length quantification (VLQ) method for local detection information (*LLR*) in cooperative sensing CR system. It is shown that the VLQ scheme which employs trade-off between detection performance and overhead volume can make the cooperative sensing more efficient, and the total overhead is maintained within a limit.

VI. APPENDIX: SIMPLIFICATION FOR LOCAL *LLR*

$$
\begin{aligned}
\frac{p\left(r_k|\mathcal{H}_1\right)}{p\left(r_k|\mathcal{H}_0\right)} &= \frac{\dfrac{1}{2}e^{-\frac{(r_k+\lambda_k)}{2}}\left(\dfrac{r_k}{\lambda_k}\right)^{\frac{M}{4}-\frac{1}{2}} I_{\frac{M}{2}-1}\left(\sqrt{r_k\lambda_k}\right)}{\dfrac{1}{2^{\frac{M}{2}}\Gamma(M/2)} r_k^{\frac{M}{2}-1} e^{-\frac{r_k}{2}}} \\
&= e^{-\frac{\lambda_k}{2}}\sum_{j=0}^{\infty}\frac{\left(\dfrac{r_k M\gamma_k}{4}\right)^j}{j!\Gamma\left(\dfrac{M}{2}+j\right)}\Gamma\left(\frac{M}{2}\right) \\
&= e^{-\frac{\lambda_k}{2}}\sum_{j=0}^{u}\frac{\left(\dfrac{r_k M\gamma_k}{4}\right)^j}{j!\Gamma\left(\dfrac{M}{2}+j\right)}\Gamma\left(\frac{M}{2}\right)+o\left(\frac{r_k M\gamma_k}{4}\right)^{u+1}
\end{aligned}
\tag{18}
$$

The sampling number M is usually large, so we assume $M \gg u$. Then, (19) can be given when $j \le u$.

$$
\begin{aligned}
\Gamma\left(\frac{M}{2}\right)\Big/\Gamma\left(\frac{M}{2}+j\right) &= \frac{M}{2}\cdot\left(\frac{M}{2}+1\right)\cdot\cdots\cdot\left(\frac{M}{2}+j-1\right) \\
&\approx \left(\frac{M}{2}\right)^j
\end{aligned}
\tag{19}
$$

Therefore, the simplified expression for *k*-th user's *LLR* is shown in equation (20).

$$
\begin{aligned}
\frac{p\left(r_k|\mathcal{H}_1\right)}{p\left(r_k|\mathcal{H}_0\right)} &\approx e^{-\frac{\lambda_k}{2}}\sum_{j=0}^{u}\frac{\left(\dfrac{r_k M\gamma_k}{4}\right)^j}{j!\left(\dfrac{M}{2}\right)^j} \\
&= e^{-\frac{\lambda_k}{2}}\sum_{j=0}^{\infty}\frac{\left(\dfrac{r_k\gamma_k}{2}\right)^j}{j!} \\
&= e^{\frac{1}{2}\gamma_k(r_k-M)} \\
&= e^{\frac{1}{2}\gamma_k M\left(\overline{r_k}-1\right)}
\end{aligned}
\tag{20}
$$

$\overline{r_k} = r_k / M_k$ indicates the average received signal for user *k*.

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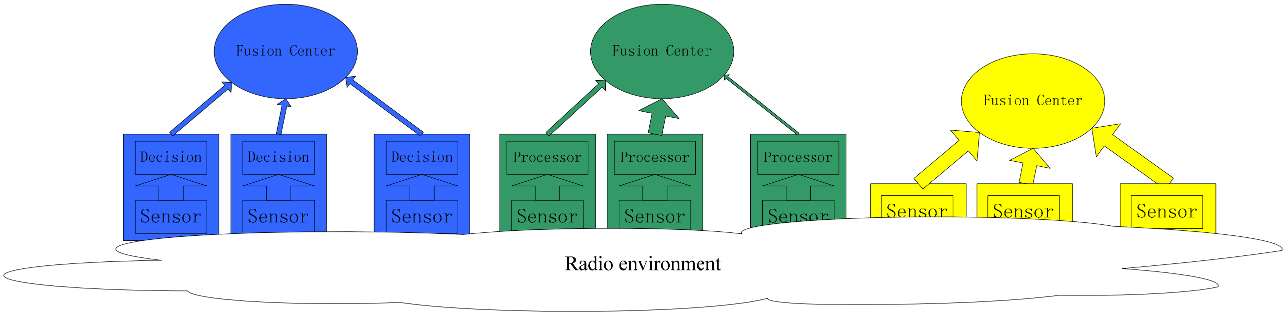

Figure 2. Three Cooperative sensing methods

REFERENCES

[1] FCC, “Spectrum Policy Task Force Report (ET Docket no.02-135),” Nov. 2002.

[2] Mitola Joseph III, Maguire Gerald Q. Jr., "Cognitive radio: making software radios more personal," *Personal Communications, IEEE*, vol. 6, pp. 13-18, 1999.

[3] Ian F. Akyildiz, Won-YeolLee, MehmetC. Vuran, Shantidev Mohanty, "A survey on spectrum management in cognitive radio networks," *Communications Magazine, IEEE,* vol. 46, pp. 40-48, 2008.

[4] Danijela Cabric, Shridhar Mubaraq Mishra, Robert W. Brodersen, "Implementation issues in spectrum sensing for cognitive radios," *in Signals, Systems and Computers, 2004. Conference Record of the Thirty-Eighth Asilomar Conference on*, 2004, pp. 772-776 Vol.1.

[5] Ghurumuruhan Ganesan and Ye (Geoffrey) Li, "Cooperative Spectrum Sensing in Cognitive Radio, Part I: Two User Networks," *Wireless Communications, IEEE Transactions on,* vol. 6, pp. 2204-2213, 2007.

[6] Ghurumuruhan Ganesan and Ye (Geoffrey) Li, "Cooperative Spectrum Sensing in Cognitive Radio, Part II: Multiuser Networks," *Wireless Communications, IEEE Transactions on,* vol. 6, pp. 2214-2222, 2007.

[7] Qian Chen, Feifei Gao, Arumugam Nallanathan and Yan Xin, "Improved Cooperative Spectrum Sensing in Cognitive Radio," *in Vehicular Technology Conference, 2008. VTC Spring 2008. IEEE*, 2008, pp. 1418-1422.

[8] Zhi Quan, Shuguang Cui and Ali H. Sayed, "An Optimal Strategy for Cooperative Spectrum Sensing in Cognitive Radio Networks An Optimal Strategy for Cooperative Spectrum Sensing in Cognitive Radio Networks," *in Global Telecommunications Conference, 2007. GLOBECOM '07. IEEE*, 2007, pp. 2947-2951

[9] Zhi Quan, Shuguang Cui and Ali H. Sayed, "Optimal Linear Cooperation for Spectrum Sensing in Cognitive Radio Networks," *Selected Topics in Signal Processing, IEEE Journal of*, vol. 2, pp. 28-40, 2008.

[10] Jun Ma and Ye (Geoffrey) Li, "Soft Combination and Detection for Cooperative Spectrum Sensing in Cognitive Radio Networks," *in Global Telecommunications Conference, 2007. GLOBECOM '07. IEEE*, 2007, pp. 3139-3143..

[11] Chunhua Sun, Wei Zhang and Khaled Ben Letaief, "Cooperative Spectrum Sensing for Cognitive Radios under Bandwidth Constraints," in *Wireless Communications and Networking Conference, 2007.WCNC 2007. IEEE*, 2007, pp. 1-5.

[12] Qun Pan, Yongyu Chang, Ruiming Zheng, Xin Zhang and Dacheng Yang, “Solution of Information Exchange for Cooperative Sensing in Cognitive Radios”, in *Wireless Communications and Networking Conference, 2009.WCNC 2009.*

[13] Edward Peh and Ying-Chang Liang, "Optimization for Cooperative Sensing in Cognitive Radio Networks," in Wireless Communications and Networking Conference, 2007.WCNC 2007. IEEE, 2007, pp. 27-32.

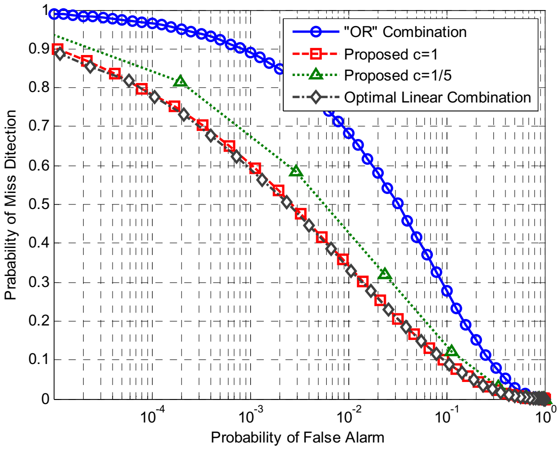

Figure 3. ROC Curves for Different Schemes

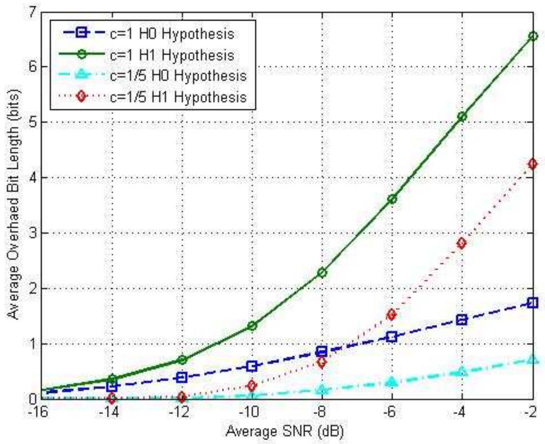

Figure 4. Average Overhead for Different Compression Ratio under Different Hypothesis

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